

# PRELIMINARY OPERATIONAL RESULTS OF THE TDRSS ONBOARD NAVIGATION SYSTEM (TONS) FOR THE TERRA MISSION

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**ABSTRACT** - *The Earth Observing System Terra spacecraft was launched on December 18, 1999, to provide data for the characterization of the terrestrial and oceanic surfaces, clouds, radiation, aerosols, and radiative balance. The Tracking and Data Relay Satellite System (TDRSS) Onboard Navigation System(ONS) (TONS) flying on Terra provides the spacecraft with an operational real-time navigation solution. TONS is a passive system that makes judicious use of Terra's communication and computer subsystems.*

*An objective of the ONS developed by NASA's Goddard Space Flight Center (GSFC) Guidance, Navigation and Control Center is to provide autonomous navigation with minimal power, weight, and volume impact on the user spacecraft. TONS relies on extracting tracking measurements onboard from a TDRSS forward-link communication signal and processing these measurements in an onboard extended Kalman filter to estimate Terra's current state. Terra is the first NASA low Earth orbiting mission to fly autonomous navigation which produces accurate results. The science orbital accuracy requirements for Terra are 150 meters (m) (3sigma) per axis with a goal of 5m (1 sigma) RSS which TONS is expected to meet. The TONS solutions are telemetered in real-time to the mission scientists along with their science data for immediate processing.*

*Once set in the operational mode, TONS eliminates the need for ground orbit determination and allows for a smooth flow from the spacecraft telemetry to planning products for the mission team. This paper will present the preliminary results of the operational TONS solution available from Terra.*

## **1 - INTRODUCTION**

Earth Observing System (EOS) AM-1, also known as Terra, was designed and developed by Lockheed Martin Corporation and launched on December 18, 1999 from the Western Test Range. On February 23, 2000, Terra achieved a polar, sun-synchronous, 705-km circular, frozen orbit, flying in constellation with Landsat-7. The navigation subsystem onboard Terra supports the mission with a prime and backup method. The backup method consists of Brouwer-Lyddane mean orbital elements (OEs) and associated rates to provide a coarse estimate of the Terra state. The TDRSS Onboard Navigation System (TONS) provides the primary operational navigation onboard Terra to meet the science accuracy requirements.

Science requirements drove Terra's need for an onboard navigation system. After successful flight demonstration on the Extreme UltraViolet Explorer (EUVE) in 1992 [Gram 94], Terra selected TONS over the Global Positioning System (GPS). Terra represents the first NASA mission to successfully fly autonomous navigation as its operational means of navigation.

TONS optimizes the use of the available communications equipment onboard Terra to measure the Doppler shift of the forward link command carrier signal from the TDRSS. The Doppler data and relevant telemetry regarding measurement validity flow to the onboard spacecraft controls computer where the data is processed through the TONS algorithms. TONS uses a sequential estimation technique to provide the Terra spacecraft with a nine-element state vector in real-time [LM SR 97]. The state vector includes: a current estimation of the six cartesian elements for position and velocity, the drag scale factor (DSF) offset to the coefficient of drag for the spacecraft, the frequency bias of the Master Oscillator (MO) used by the spacecraft for signal reference and clock definition, and a data measurement bias. Onboard, the TONS state provides a high fidelity reference for the attitude subsystem and autonomous forward signal acquisition. Scientists obtain the accurate TONS state vector in the downlinked telemetry, thereby eliminating the need for post-processed definitive solutions. Scientists also receive the TONS data via ancillary data to their instruments thereby allowing the instruments to use the navigation data with no human intervention. Additionally, the EOS Operation Center (EOC) inputs the TONS state vector to produce planning and scheduling products, maneuver planning and calibration, and daily backup OE uploads for Terra. To support Terra's TDRSS communications and navigation, TDRS state vectors and OEs are uploaded daily based on an ephemeris provided by GSFC's Multi-Mission Flight Dynamics (MMFD) group. This paper will highlight the operational performance of the Terra onboard navigation system for the first three months after launch.

## **2 - OPERATIONAL REQUIREMENTS AND IMPLEMENTATION**

The proto-flight software from the EUVE experiment was provided to the spacecraft manufacturer and used as the heritage code for the Terra implementation of TONS. Terra's navigation subsystem has two main modes, Backup and Normal. Each mode provides orbital parameters for Terra and the four TDRS spacecraft usable by Terra at any given time. The Backup mode provides the spacecraft with coarse orbital information to maintain communication signal acquisition and attitude control, and antenna pointing. Six Brouwer-Lyddane elements and two rates provide Terra information while for the four TDRSSs, there are the six elements and only one rate. These orbital elements are uploaded daily and are valid for two days onboard. The OEs also provide a coarse check on the TONS estimate of the Terra state and TDRS propagated states to ensure a failure in the TONS solution will not adversely effect the attitude subsystem. If TONS is determined to be out of tolerance, the onboard system will automatically switch to OEs as the navigation output.

Normal mode provides real-time accurate state information for Terra via the TONS. TONS software is divided into two submodes: Propagation and Filter. In both submodes daily state vectors and modeling data (mass and the coefficient of radiation) are uploaded for each of the four TDRS spacecraft used by Terra and then propagated onboard. In Propagate submode, the Terra state vector and modeling information (mass and the coefficient of drag) are uploaded to the spacecraft and propagated onboard. In Filter submode, real-time Doppler data provides measurements to update the Terra state, therefore eliminating the need to perform orbit determinations on the ground and upload the resultant state vector daily. Measurements are available to the Filter every 16.384 seconds (sec) during a TDRSS contact. In between measurement updates, TONS propagates the Terra state. All science requirements are met in Filter submode and this is the prime operational mode.

The science requirements were derived to ensure maintenance to the World Reference Grid, accurate node crossing information, high fidelity attitude guidance, and science data resolution. Table 1 summarizes the requirements for the Terra navigation subsystem discussed in this paper.

**Table 1.** Terra Navigation Accuracy Requirements Summary

Parameter	Requirement
Terra Backup Orbital Elements	50 km, RSS, 3 sigma after 2 days
TDRS Backup Orbital Elements	120 km, RSS, 3 sigma after 2 days
Frequency Control Words	less than +/- 1500 Hz, 3 sigma
TONS Terra Position	150 m, per axis, 3 sigma GOAL: 5m, RSS, 1 sigma
TONS Terra Crosstrack Velocity	0.16 m/s, 3 sigma
TONS TDRS Position	75 m, 3 sigma, after 1 day propagated onboard
TONS TDRS Velocity	0.055 m/s, 3 sigma, after 1 day propagated onboard
Transponder Doppler Random Noise	0.0066 Hz
Transponder Doppler System Timing Error	+/- 1 microsecond

As the operational system on Terra, TONS was developed to meet the requirements under various operational scenarios. These scenarios include: MO adjustments as required to maintain the spacecraft clock; small stationkeeping maneuvers to maintain the Terra ground-track; TDRS maneuvers; leap second adjustments; and daily state and OE uploads. TONS was not designed to meet the requirements through large maneuvers such as ascent or inclination-change maneuvers.

The Doppler data measured by Terra comes from the fixed frequency forward communications signal that emanates at a TDRSS ground station based on the TDRSS standard reference. Terra's ultrastable oscillator provides the reference to the transponder that passively measures the Doppler. The transponder must be given a command to offset the receiver in order to acquire the uncompensated forward TDRSS signal. The command, known as a frequency control word (FCW), comes from the current estimate of the Doppler between Terra and TDRSS based on the onboard states. To provide the highest quality Doppler data to achieve the mission requirements, all timing onboard Terra is derived from the ultrastable Master Oscillator. In order to meet the requirements, system timing must be steered to within +/- 100 microseconds with TONS providing clock knowledge to +/- 10 microseconds. In turn, this means the Doppler data must be ontime to within +/- 1 microsecond from the transponder. The Command and Telemetry Interface Unit (CTIU) monitors the Doppler Sample Mark provided by the transponder to ensure the Doppler timing accuracy.

Prior to TONS being declared operational, the MMFD provided orbit determination services to Terra based on traditional TDRSS tracking data received at MMFD. MMFD provided post-launch and post-maneuver solutions as well as daily orbit determination based on a batch least-squares fit to the data. Each definitive solution was then propagated for 50 days using the TONS dynamic modeling, which includes a Harris-Priester atmospheric model with solar flux of 200, a 30x30 JGM-2 geopotential model, and states represented in J2000 coordinates. The results presented in this paper are comparisons of the onboard navigation data to that obtained from MMFD orbit solutions. These comparisons were performed using the TONS Ground Support System (TGSS) [Godd 99] located in the EOC.

Daily uploads to Terra nominally occur at 1900z. Initially, these uploads included OEs for Terra and the four TDRSs as well as a UTC-UT1 offset and MO bias. As Terra transitioned to Normal Mode/Propagate submode, TDRS state vectors and modeling tables, and a Terra state vector and modeling table were added to the upload. Once Terra transitioned to Filter submode, the daily

uploads of the Terra state and model tables as well as the MO bias table were discontinued, since these quantities were now being estimated onboard.

## 2 – EARLY MISSION

After MMFD performed the post-launch orbit solution, initial OEs were uploaded for Terra and the four TDRSs. The uploads allowed Backup mode to support both attitude knowledge and TDRSS communications. Since that time, OE position and velocity telemetry from Terra and the four TDRSs have been compared to the MMFD solutions and consistently show that the OEs are meeting the accuracy requirements in Table 1. Terra OEs compare from 12 to 22 km in position, while TDRS OEs compare from 1 to 10 km in position.

Terra transitioned to Normal mode/Propagation submode on January 3, 2000, and after a 24-hour checkout period transitioned the output from OEs to the TONS propagated solution. The next step to achieving science configuration came when onboard autonomous signal acquisition, via frequency control words to the transponder, was enabled later in the day on January 4. However, due to an anomaly with the High Gain Antenna, Terra switched back to using the omni antennas and the FCWs were disabled. The FCWs were re-enabled on January 13, 2000, with Terra flying autonomous acquisition of the TDRSS signals since then. Whether in Backup or Normal mode, FCWs to offset the receiver have consistently oscillated within  $\pm 200$  Hz of the actual Doppler shifted receive frequency. The ground-to-inclined TDRS Doppler shift is not modeled in the FCW computation in the ground support system, and explains the 24-hour oscillation difference. The FCWs onboard Terra performed more accurately than the comparison data indicates.

Terra navigation remained in Normal mode/Propagate submode until February 7, 2000. The output telemetry used by the spacecraft toggled back to the OEs during periods of ascent maneuvers and early Filter submode checkout, January 10 to 15, 2000 and February 3 to 24, 2000.

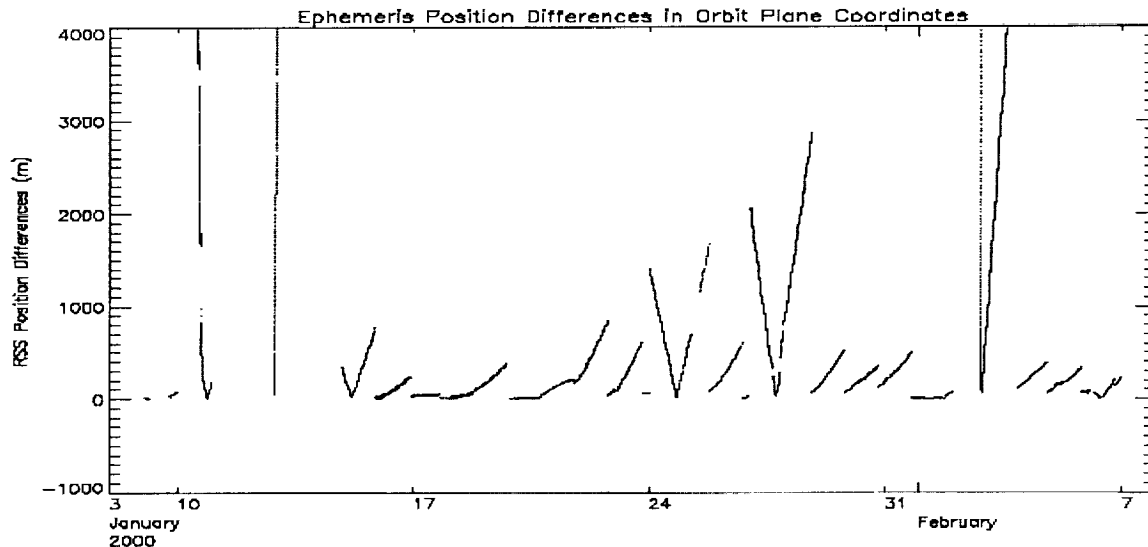


Fig 1. Comparison of TONS Propagation to MMFD Definitive

Throughout the one month of pure propagations, the TONS-propagated Terra state nominally compared to the MMFD definitive solution between 100m and 1km in position (Figure 1) and 0.12m/s and 1m/s in velocity. The plot in Figure 1 clearly displays the daily synchronization to a newly uploaded Terra state vector and the comparison difference growth between the two sets of states. The spikes occurring January 10-14, 2000 were induced by a spacecraft hardware anomaly outside the navigation subsystem. This left the spacecraft controls computer in an off-nominal configuration for several days. As a by-product of that configuration false thruster firings were

indicated to TONS, perturbing the state. On January 25 and 27, the large comparisons were due to poor definitive MMFD solutions over those days. On February 2, Terra performed two 20-second propulsive hardware burns which influenced the definitive solution over the timespan.

## 2.1- TDRS States

The TDRS states are propagated onboard with perturbation modeling reduced to an 8x8 Joint Gravity Model-2 geopotential and solar radiation pressure. In order to meet the Terra orbit accuracy requirements, MMFD provides definitive solutions for each TDRS and models stationkeeping and momentumunload maneuvers in the predicted ephemeris. This allows the Flight Operations Team (FOT) to upload a more accurate TDRS state after a modeled momentum unload maneuver occurs. In the case of stationkeeping maneuvers, MMFD also provides the EOC with a post-maneuver orbit solution within 4.5 hours after the TDRS maneuver. Over the timespan discussed in this paper, the TDRS states have routinely maintained their accuracy requirement with only a few exceptions when a short-notice momentum unload was not modeled in the predicted ephemeris. The limit does not affect navigation support of communications and antenna pointing.

TDRS state table loads incorporate a time limit nominally set at 48 hours, or adjusted based on predicted maneuver knowledge. The time limit prevents the use of the propagated TDRS state for navigation filter processing until a new TDRS state is uploaded.

## 2.2 – Clock Error

After an initial clock adjust of  $-2.143$  seconds three days after launch, further refinement was needed to ensure system requirements. However, the operational system for clock calibration was unable to resolve the ambiguity between the cycle data used to determine the clock offset. While TONS was in Propagate submode, the Doppler residuals measured onboard were plotted against Doppler rate to obtain a timing error in the Doppler observation. Doppler timing error was used to assist the clock calibration engineers in resolving the cycle data ambiguity and setting the clock. Figure 2 shows the results of timing error analysis obtained from TONS. Two additional clock adjusts were performed based on the data from the TONS Doppler residuals. The use of TONS to support on-orbit clock correlation was an unanticipated benefit of the onboard Doppler measurement processing.

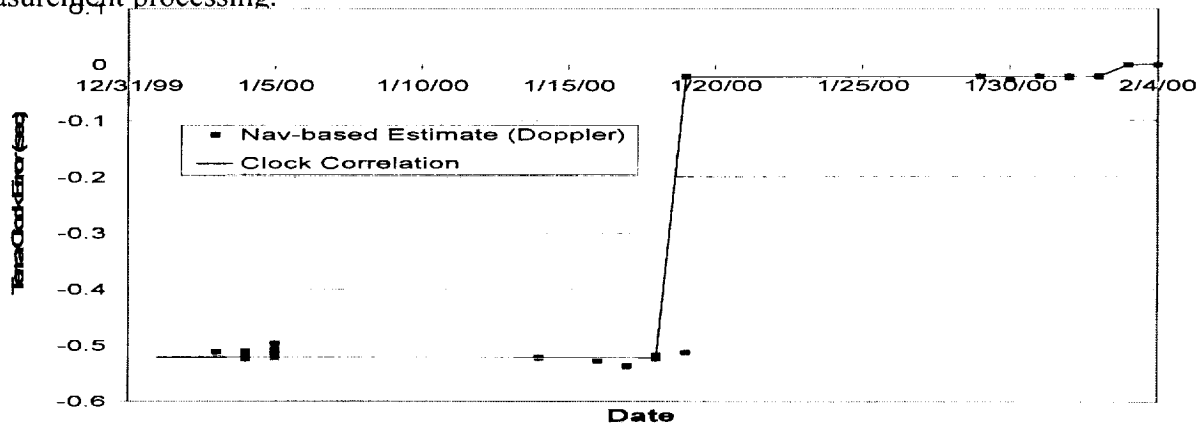


Fig. 2 Timing Error From Doppler Residuals And Clock Correlation

## 3 – FILTER SUBMODE CONVERGENCE

On February 7, 2000, TONS transitioned to Filter submode. Since Terra was undergoing ascent maneuvers, the spacecraft continued to fly off the OEs during the TONS Filter check-out. TONS

met the convergence criteria within 1.5 hours after initialization. The convergence covariance indications include: Root Sum Square Position Sigma less than 100 m, Root Sum Square Velocity Sigma less than 0.11 m/s; Semi-Major Axis Sigma less than 5 m; and MO Bias Sigma less than 0.4 Hz at S-band. After 1.5 hours over which TONS processed 45 minutes of forward link Doppler data, TONS matched the MMFD definitive solution to within 20 m. TONS showed consistent steady-state results within 9 hours, after the estimate of the drag scale factor reached steady state. Position differences to the MMFD definitive solution at this time reduced to 12 m. Figure 3 shows position comparison with the MMFD definitive solution over the initial convergence period for TONS.

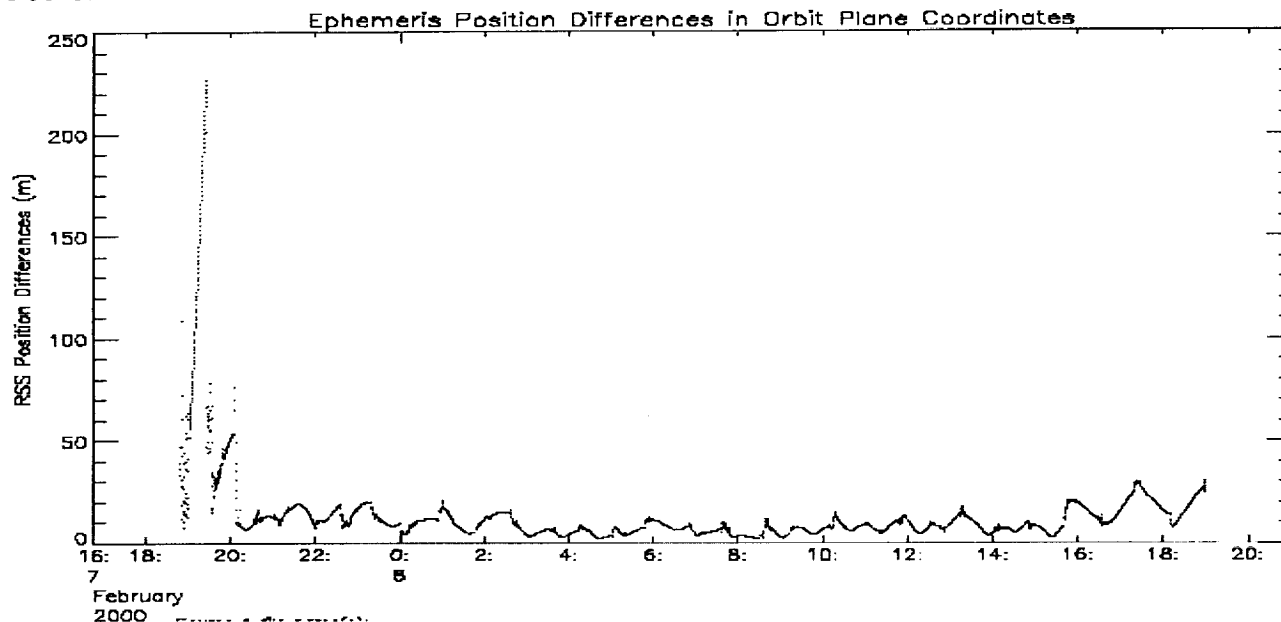


Fig 3. TONS Filter Convergence

#### 4 – PRELIMINARY FILTER OPERATIONS

To obtain high accuracy navigation results using one-way Doppler, the measurements must be of high quality. The determining factors are the reference frequency and the measurement method. The MO supplied the reference for the transponder and was specified to be stable to better than  $1 \times 10^{-10}$  parts per day. The MO was monitored from launch using the Local Oscillator Frequency (LOF) solution based on one-way return Doppler data obtained at MMFD. Figure 4 plots the MO trend results and shows that the MO stability is within specification.

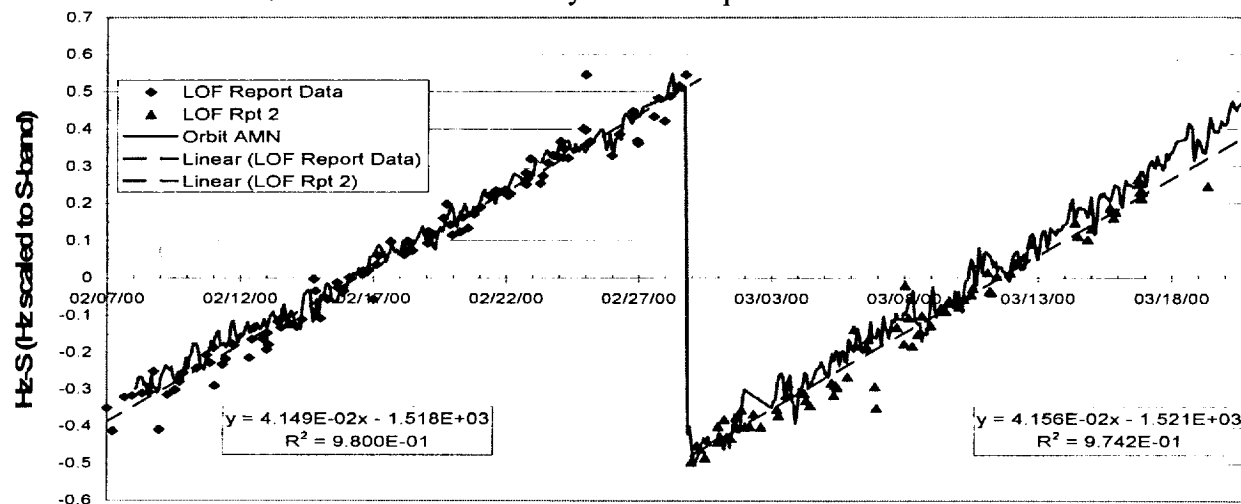
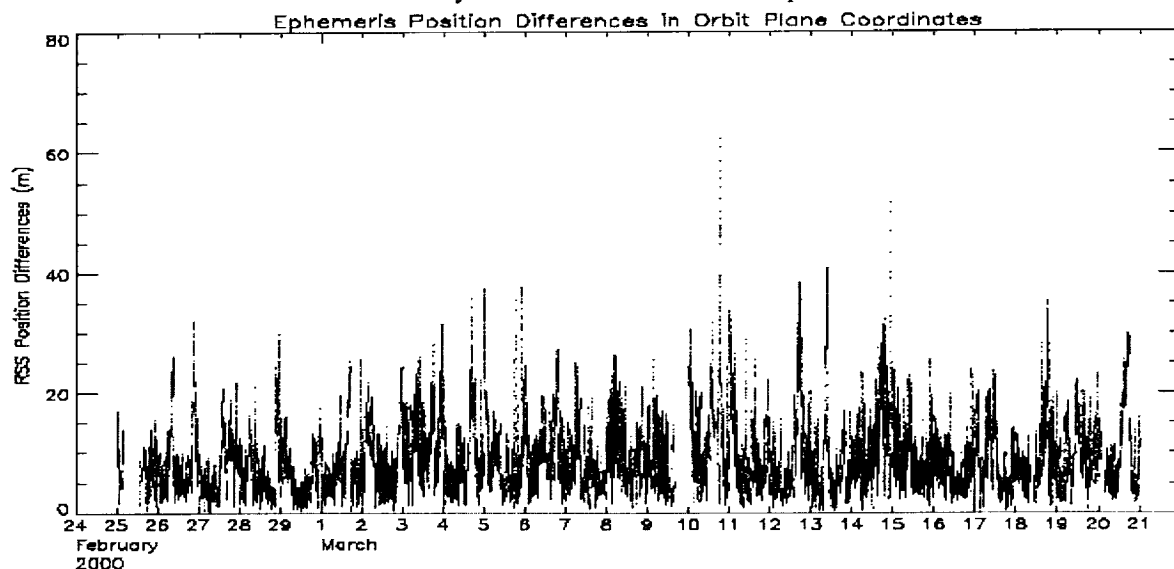


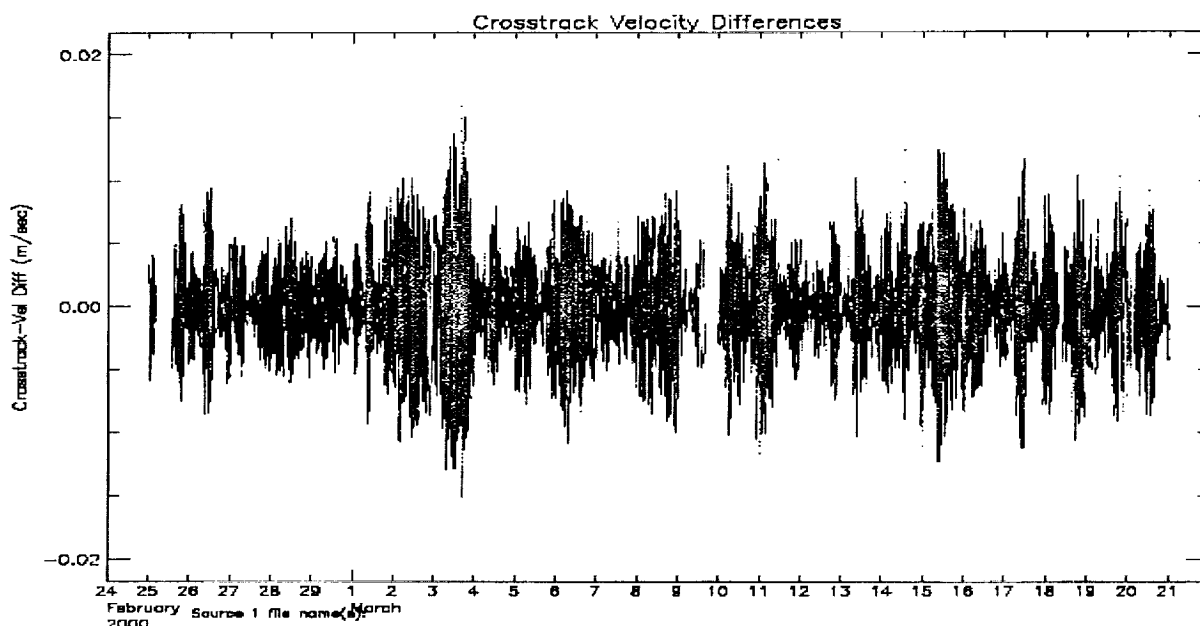
Fig 4. Master Oscillator Bias and Drift Data

The MO operates within specification thus leaving the onus on the transponder to provide low noise non-destruct Doppler measurements. A sixth-order Variate Difference Noise Analysis (VDNA) algorithm was used to characterize the quality of the Doppler data. The results indicate that 95 percent of the time the noise is within the specification in Table 1. However, the results are tainted by the inclusion of low elevation passes through the ionosphere which add significant noise to the Doppler data, raising the overall statistics for noise analysis and reducing the percentage of data within specification..

As of this writing, the TONS Filter has operated flawlessly for almost three months providing spectacular results. Daily comparisons made of the TONS solution to the MMFD definitive solution show that the TONS filter matches MMFD to within 40 m RSS (3 sigma) in position and 0.016 m/s (3 sigma) in crosstrack velocity, as shown in Figures 5 and 6. At this level, it is likely that a large portion of the difference is due to the differences in orbit determination methodology. The batch least squares solution used by MMFD tends to fit better to data in the middle of the span than on the ends, whereas the sequential estimation method employed by TONS provides more consistent orbit solutions stimulated by constant measurement updates.



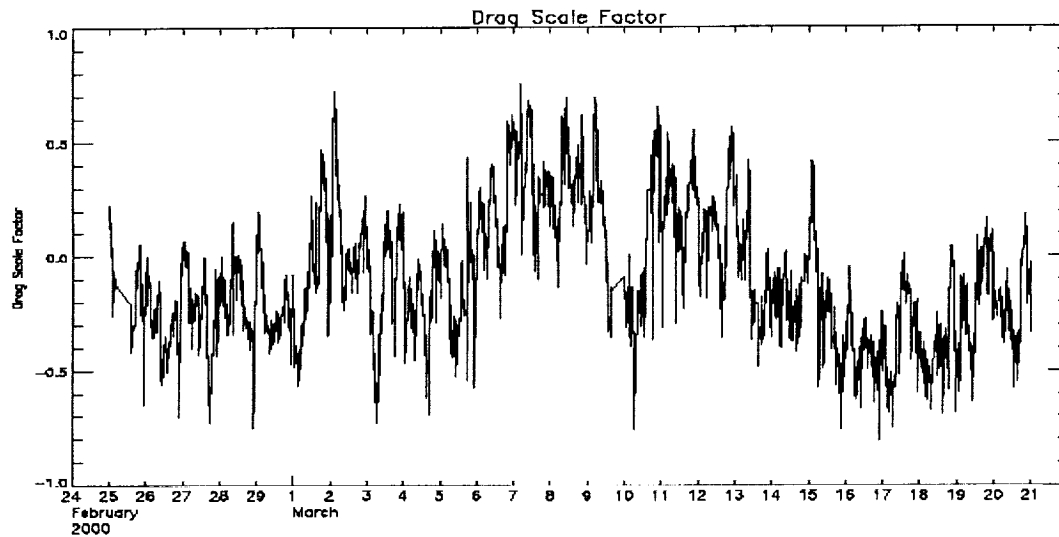
**Fig 5a** TONS Filter Position Differences Compared to MMFD Definitive



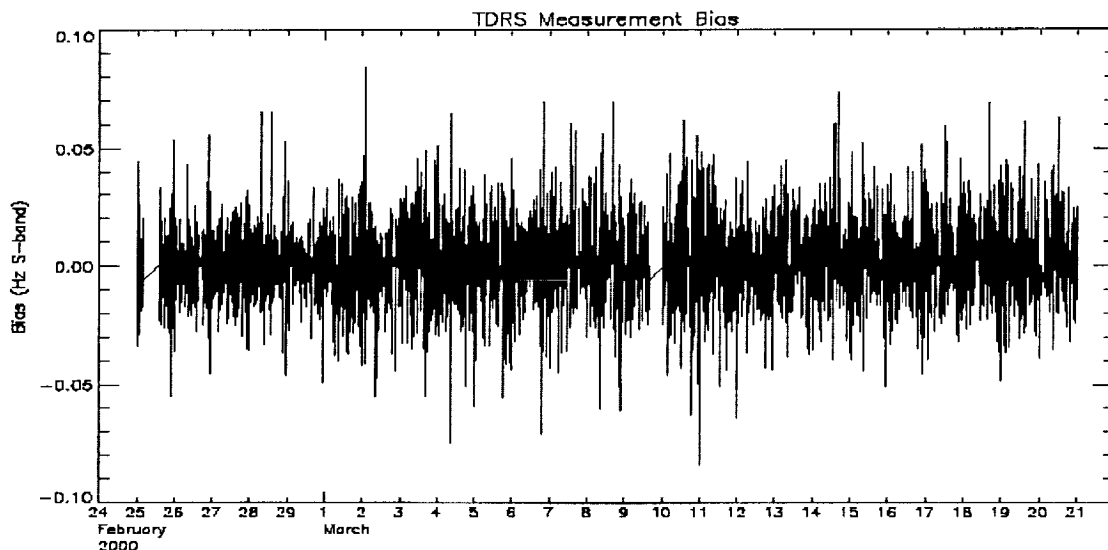
**Fig 6.** TONS Filter Crosstrack Velocity Differences Compared to MMFD Definitive

TDRS-to-Terra geometry coupled with view period constraints results in two periods per day with several low elevation contacts in a row. The TONS state difference from MMFD and the TONS RSS Position Sigma both increase during these times, but show immediate recovery with the next higher elevation contact. The maximum differences in Figure 5 occur during these contacts with the exception of the spike on March 14, 2000 which was the result of a Terra stationkeeping maneuver.

Figure 7 displays the drag scale factor (DSF) estimated by TONS as a correction to the coefficient of drag. These results occur at the peak of the solar cycle, hence they show the large fluctuations expected during this timeframe. MMFD solves for a similar parameter in their orbit solutions, called rho-1. However, the solution provides one value over the entire definitive span. The DSF is updated with every valid Doppler measurement. Comparison between rho-1 from MMFD and DSF from TONS indicates similar daily trends over the long term.



**Fig 7. Drag Scale Factor Estimated by TONS**



**Fig 8. TDRS Measurement Bias Estimated by TONS**

Figure 8 shows the measurement bias estimated by the TONS filter. The measurement bias resets with each new communications contact. Currently, the TDRS measurement bias absorbs any unmodeled biases as seen in the data during a contact. During the low elevation contacts, the TDRS measurement bias increases slightly indicating a disturbance in the data.



Estimation of the MO frequency bias is easily influenced by variations in the data as well. Figure 4 above shows the TONS estimate of the MO bias since filter initialization plotted along with the MMFD estimate of the MO frequency bias. The discontinuity between the two segments represents an MO frequency adjust. For the MO adjust, the FOT loads a new absolute frequency value to the MO. This command is coordinated with an “ADJUST” command sent to the navigation software to prevent excessive filter disturbances. The command adjusts the MO frequency estimate in the TONS state and increases the corresponding filter variance. Additionally, an upload table provides the new MO drift rate and clock offset from UTC to the navigation software.

The first segment of data, up until March 1, 2000, shows a close match between MMFD and TONS. After March 1, the TONS estimate is higher, the cause for which is under investigation. Incorrectly estimating the MO frequency bias directly effects the propagation of the clock offset from UTC. This induces the need for more frequent table loads to reinitialize the clock error propagation. However, the slightly high estimate of the MO frequency by TONS results in little or no impact on TONS state accuracy.

## 5 – FILTER PERFORMANCE DURING MANEUVERS

TONS includes a burn model based on thruster commands and yaw offset. The model incorporates maneuver accelerations over the last update interval and applies the forces to the Terra state estimate. During the maneuver, measurement updates are disabled via command and re-enabled soon after the maneuver ends. Once post-burn measurement updates begin, TONS meets all the convergence criteria within one orbit. No post-maneuver state loads are required because the TONS estimate following the burn has proven accurate, even for the larger ascent maneuvers. However, the ground system does supply TONS with a post-maneuver mass estimate for Terra to promote propagation accuracy when Doppler measurements are not available. Table 2 provides TONS filter performance data for all ascent maneuvers and two stationkeeping maneuvers.

**Table 2.** TONS Filter Performance During Maneuvers

#	Burn Dur (s)	Max RSS 1sig uncertainty after burn			Max post burn ephem error vs MMFD def.	
		POS(m)	VEL(m/s)	SMA(m)	POS(m)	VEL(m/s)
1	60	242.18	0.2802	111.23	140.0	0.18
2	150	630.90	0.7785	284.86	389.1	0.49
3	300	1338.50	1.6244	562.93	920.0	1.12
4	320	1411.60	1.7044	584.39	960.0	1.20
5	320	827.20	1.0092	568.57	570.0	0.70
6	320	344.74	0.4213	552.30	150.0	0.20
7	280	300.09	0.3641	471.00	125.0	0.21
8	110	228.15	0.2344	175.83	42.0	0.05
9	21.379	103.75	0.1063	30.43	52.0	0.05
10	26.000	105.90	0.1227	37.12	60.0	0.06

The burn model only applies to the TONS state estimate. The backup OEs require a predicted post-maneuver set of elements that are held onboard until the maneuver ends. Although the operational procedure kept the OEs as output for the first nine maneuvers, the TONS performance far exceeded the coarse navigation provided by the OEs. During the stationkeeping maneuvers, TONS state estimates were well within the accuracy requirements given in Table 1. Therefore, starting with maneuver 10, the operational procedure changed to keep TONS as output across the maneuver. This procedure change reduced the operational complexity of maneuvers and improved recovery time to science mode. Terra science operations are impacted for only four hours around a stationkeeping maneuver. This is exceptional for a science mission of Terra’s type and due in large part to the autonomous navigation onboard Terra.

## 6 – FUTURE FILTER TUNING ANALYSIS

Although TONS performance has been admirable and well within the requirements, the Terra science team would like increased performance from TONS. Since the Doppler has been found to be severely corrupted during low elevation passes, analysis is underway to evaluate a trade-off of having more data of poorer quality versus less data of higher quality by raising the elevation angle limit in the filter. This limit effectively filters out all the data below a specified elevation angle between Terra and the TDRS which has been potentially corrupted by the ionosphere.

The original filter tuning design kept the DSF, MO Frequency Bias, and TDRS Measurement Bias very open to accommodate a wide range of orbital events and physical conditions. To achieve maximum accuracy, analysis is planned to investigate a different set of tuning parameters. The new tuning should reflect greater confidence in the Doppler measurements as determined throughout the mission. The state process noise for the TDRS Measurement Bias should be adjusted to allow more measurement-related variations to be absorbed while the process noise for the MO should be adjusted down to reflect the operational performance of the MO stability.

Planned analysis will identify whether increased performance may also be achieved by restricting the DSF state process noise. Although tightening the DSF state process noise may leave the filter vulnerable to large geomagnetic storms, it may also provide a cleaner estimate that more closely relates to the atmospheric performance overall.

Additionally, planned analysis will determine whether increasing the measurement weight during a maneuver can assist the filter in terms of state estimation across the maneuver or state recovery after the maneuver. Performance may be increased to the level where navigation science accuracy requirements are maintained throughout all maneuvers.

## 7 – CONCLUSIONS

The TONS implementation on Terra is a phenomenal success. TONS estimates exceed all state vector accuracy requirements and show progress toward meeting the navigation accuracy goal set by the science team. As NASA's first operational autonomous onboard navigation system, Terra's TONS represents a big step forward in enabling technologies for future missions, particularly those in the formation flying realm.

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